V. "On Some Phenomena connected with Cloudy Condensation." By John Aitken, F.R.S. Received March 2, 1892.

In the first part of this communication I intend giving the results of an investigation into the phenomena connected with the cloudy condensation produced when a jet of steam mixes with ordinary air, with special reference to the marked change which takes place in the appearance of the jet by electrification and other causes. In the second part will be given the results of an investigation into certain colour phenomena which can be produced when the condensation is made to take place under certain conditions, and it is thought that these experimental colour phenomena, if they do not give the explanation of a "green sun," at least enable us to reproduce it artificially with the materials existing in our atmosphere.

Part I.—Steam Jets.

When a jet of steam escapes into the air, condensation at once ensues by the expansion and the mixing of the steam with the cold air. The result is the jet becomes distinctly visible by the light reflected by the minute drops of water carried along in the mixed gases and vapour. At first sight there is little that is interesting in the changes then taking place. The subject has, therefore, attracted but little attention, and has been but little studied. This is evident from the great interest that has been taken in the change produced in the appearance of the jet when it is electrified; yet I hope to be able to show that this is only one of a number of causes which alter the appearance of the condensing steam.

R. Helmholtz was the first to show that when an ordinary jet of steam is electrified, there is a marked increase in the density of the condensation. The effect of the electricity is certainly very remarkable. The instant the jet is electrified, it at once changes and becomes much denser, and the condensed particles also become visible much closer up to the nozzle from which the steam is escaping. For the convenience of description we shall call this second form of condensation *dense condensation*, while that usually observed we shall call *ordinary condensation*. Not that there is any hard and fast line between these two forms, as the one may be made to change by imperceptible degrees into the other. All that is meant is that the one is dense compared with the other.

One result of this investigation is that, in addition to electrification of the jet, there are four other ways in which the ordinary condensa-

tion may be changed into the dense form. These five ways of changing the ordinary into the dense form of condensation are :—

1. Electrification of the jet.
2. An increase in the number of dust nuclei.
3. Cold or low temperature of the air.
4. High pressure of the steam.
5. Obstructions in front of the jet and rough or irregular nozzles.

We shall now describe some experiments to illustrate each of these different ways of causing the ordinary condensation to change and take the dense form. In the experiments to be described, the steam was generally generated in a copper boiler, which could be pressed up to fully one atmosphere. The nozzle from which the steam escaped was placed at some distance from the boiler to prevent the hot gases influencing the jet. The steam was conveyed by means of a metal pipe to the nozzle, and a water trap was placed near the end of this pipe to prevent the irregularities which would be produced if the water condensed in the pipe were allowed to issue from the nozzle. The nozzle generally used was made of brass, carefully bored to a diameter of 1 mm., the diameter of the bore widening inwards, while the outside of the nozzle was turned to a fine edge in front. With this apparatus most of the experiments were made, but occasionally glass vessels and nozzles were used, as well as vessels and nozzles of other materials, but with no marked difference in the results.

1. *Electrification.*

In the experiments with electricity only steam of a low pressure should be used. The reason of this will be understood from what follows under division 4. In these experiments slight electrification was used, as only an old-fashioned cylinder electrical machine was available for the purpose, and in the damp atmosphere produced by the steam jet the electrification was only capable of giving a spark of about 1 cm. or generally less.

The necessary condition for the electricity producing any effect on the jet is that the particles in the jet be electrified either by direct discharge or by an induction discharge. The mere presence of an electrified body near the jet has no influence whatever. In order that it may have an effect, the electrified body must terminate in a point placed near the jet, and the potential must be great enough to cause a discharge of the electricity to the jet. When this takes place the jet at once becomes dense and remains in that condition while the discharge continues. The electrified body may, however, electrify the jet by induction. If, for instance, the electrified body be a sphere, and the nozzle from which the steam is issuing be pointed, the electricity discharged by the nozzle will electrify the

particles, and the condensation becomes dense. But if the nozzle be not pointed, then the presence of the electrified body produces no change, as there is no discharge of electricity. But if now we hold a needle or other pointed conductor near the jet issuing from the rounded nozzle it at once becomes dense, by the induction discharge from the point. In place of a point in the last experiment, we may use a flame; in fact, we may use any influence which will enable the electrified body to electrify the particles in the jet.

Another way of making this experiment is to insulate the boiler, and electrify it. If the nozzle be pointed, the jet becomes dense on electrification; but, if it be rounded, the electrification has no effect. If, however, we bring a needle or a flame near the rounded nozzle, the jet becomes dense. To get no effect from the electrification it is necessary that the nozzle be a ball of some size, the orifice through which the steam issues being, of course, the same diameter as that of the pointed jet.

The effect of the electrification has been studied by R. Helmholtz and by Mr. Shelford Bidwell,* but neither of them seems to be satisfied with any explanation they offer. Mr. Bidwell, from a spectroscopic examination of the light transmitted through the jet under the two conditions, came to the conclusion that in the dense condition the particles were larger than in the ordinary form of condensation; and he thinks that the increase in size is due to the electricity causing the small drops of water to coalesce and form larger drops. In support of this explanation, he quotes Lord Rayleigh's experiments on the coalescence of drops in water jets while under the influence of electricity. As Mr. Bidwell does not put forth this opinion as final, there is less reason for hesitation in stating that the conclusion I have come to is diametrically opposed to Mr. Bidwell's.

There seems to be no doubt that electricity will act on these very small drops of water in the same way as it acts on the drops in a jet of water. That its action is similar is easily proved by the following experiment with mist drops:—Take a small open vessel full of hot water—it is better to colour the water nearly black for convenience of observation—a cup of tea without cream does very well for the purpose. Place the cup on a table between the window and the observer. On now looking at the cup from such a position that no bright light is reflected from the surface of the liquid, there will be seen what looks like scum on the surface of the tea. That scum is, however, only a multitude of small mist-drops which have condensed out of the rising steam and have fallen on the surface of the liquid, where they are seen floating. If now we take a piece of brown paper, or any convenient material, and rub it slightly and hold it over the cup, the "scum" will disappear at once, and be replaced by other drops

* 'Phil. Mag.,' February 1890.

when the electrified body is removed. As in Lord Rayleigh's experiments, a very feeble electrification is sufficient to cause the absorption of the drops into the body of the liquid. It is therefore not because there is supposed to be any difference in the action of electricity on large and on very small drops that a different conclusion from Mr. Bidwell's has been arrived at, but because all the experiments to be described point to the conclusion that the dense form of condensation is not due to an increase in the size of the drops, but to an increase in the number, accompanied of course by a diminution in the size.

We may suppose the following to be something like the manner in which the electricity acts on the jet:—In a steam jet the rapid movements of the drops give rise to frequent collisions, and these result in the coalescence of many of the drops, so that each drop in ordinary condensation is made up of a number; but, when the jet is electrified, the electrification prevents the particles coming into contact, as they repel each other, and the consequence is, we have a greater number of particles in a dense and electrified jet than in an ordinary one.

Lord Rayleigh's experiments on the action of electricity on water jets support this view. He has shown that, in order to produce coalescence, the electrification must be very slight, and he also points out that the coalescence does not seem to be so much due to electrification as to a difference of electrification, which would appear to cause a discharge of electricity to take place between the drops, which ruptures the films, so causing contact. Further, he has shown that when the electrification is strong, and the conditions are such that the drops become electrified, the effect is diametrically the opposite, and instead of coalescence, the particles now scatter far more than the unelectrified drops. Now from the conditions of the experiments with electrified steam jets it is evident that the drops are electrified, and are in the same condition as the electrified scattering water jet. We are, therefore, entitled to expect that the electricity will prevent and not aid the coalescence of the small drops in the steam jet.

Other considerations also point to the increase in the density of the jet being due to an increase and not to a diminution in the number of drops. We know that if we blow steam into air, that the fewer dust nuclei there are in the air, the thinner is the condensation, and when the dust is nearly all out of the air, only a fine rain falls which can scarcely be detected by the unaided eye. Further, the evidence from condensation produced by expanding moist air points to the same conclusion, namely, that the more dust particles there are in the air, the denser is the condensation when cooled by expansion, and the purer the air is, the thinner is the cloud.* These experiments all

* 'Trans. Roy. Soc. Edinburgh,' vol. 30, Part I, p. 340.

point to the conclusion that the dense form of condensation is due to a large number of water drops, and the thinner form to a smaller number, though of greater individual size. The only condition under which it seems probable that the increase in number will not give rise to increase in density is when the particles are so small that they are unable to reflect waves of any colour of light. So far as has yet been observed this never happens. However slight the amount of expansion, the greater number of particles always gives the denser form of condensation.

The action of the electricity on the jet does not appear to be anything positive: it rather seems to prevent something which takes place under ordinary conditions. For instance, electricity has no effect in thickening the cloud of so-called steam rising from a hot and wet surface. The electrically driven current of air from a point when directed to the steaming surface has no effect whatever on the density of the condensation. Nor has electricity any effect on the steam rising from an open vessel. The small drops of water under these conditions move but slowly, and there is but little tendency for them to come into collision with each other; there are, therefore, few collisions for the electricity to prevent, and little or no thickening is produced by electrification under those conditions. Further on we shall have frequent opportunities of seeing that the dense form of condensation is the result of an increase in the number of particles, and that whatever gives rise to an increase in the number causes an increase in the density.

When the jet is electrified and becomes dense, it has been noticed by others that it emits at the same time a peculiar sound, and I find that whenever the jet becomes dense, from whatever cause, it begins "to speak." But when the density is due to electrification, the sound is, however, slightly different from the sound emitted when dense from any of the other causes. When dense from causes other than electrification, the sound is similar to that produced by the jet striking an obstruction; but when electrified, the sound is a combination of this sound with another due to the discharge of the electricity; and this second sound depends on the manner in which the electric discharge takes place. If the discharging point is not sharp, and the potential is just sufficient to cause discharge, then the discharge is not continuous, but takes place at short intervals; it becomes, in fact, a series of disruptive discharges, and gives rise to a fluttering noise. This fluttering sound is greatly increased if the point terminates in a small ball of about 1 mm. diameter, and it is entirely abolished if we use a very sharp point, or better, a flame. The discharge with either the very sharp point or the flame is perfectly continuous, and nothing but the slight hissing that accompanies all dense forms of condensation is heard when the jet is electrified.

It has generally been stated that the effect of the electrification is sudden and marked, that whenever the jet is electrified it at once becomes very dense. This, however, is due to the manner in which the jet has generally been electrified. Some degree of potential is necessary to produce a discharge from the point, and whenever the potential is high enough to cause this, it is sufficient to charge the drops high enough to give rise to a very dense condensation. But if we make the discharging point extremely fine, or assist the discharge by means of a flame, then, we may begin with electricity of a very low potential, and the increase in the density may be made to begin by almost imperceptible degrees and to increase slowly to the dense form by gradually increasing the potential.

We shall for the present leave the question of the effect of the ordinary and the dense forms of condensation on the light transmitted through them, as it will be better discussed after we have considered all the ways in which the jet may be made dense, and we shall now pass on to consider the second of those given in our list.

2. *An Increase in the Number of Dust Nuclei.*

It has been noticed by previous observers that a flame brought near the jet tended to make the condensation dense; but, in describing the experiments, a confusion has generally been made between the flame and the products of the combustion taking place in the flame. So far as I have been able to observe, flame has no effect on the density of the condensation. Neither a luminous flame nor the flame of a Bunsen burner has any effect so long as the products of combustion are kept away from the jet. But if the products are drawn into the jet, they have a very marked effect either in increasing or decreasing the density. If the flame is near and the gases are hot, they make the jet nearly invisible, but if the gases are cooled or are not in great quantity, then they make the jet as dense as if it were electrified. The simplest way of studying this latter effect is to bring the products of combustion to the jet by means of a metal tube 2 or 3 cm. in diameter and about $\frac{1}{2}$ a metre long. A small flame about $\frac{1}{2}$ cm. high, placed below the level of the jet, is used. One end of the tube is kept over the flame while the other can be brought near the nozzle. It will be found that when brought into that position the jet will at once become dense, and when it is removed it will return to its ordinary condition, and become dense again with every return of the impure gases.

The increase in density in this case is due to the greater number of dust particles in the gases offering a greater number of nuclei for condensation, and the result is a great increase in the number of water particles, and consequent thickening of the condensation, a

result which, as has already been stated, the author proved some years ago.

The change in the appearance of the jet when the products of combustion are brought to it, is exactly the same as that produced by electrification. The whole jet becomes dense, the condensed particles are visible nearly up to the nozzle, and the jet makes the same sound as when electrified by silent discharge, and further, electricity of the potential used does not make it any denser.

It seems probable that the very great number of dust particles in the products of combustion act in two ways: first, by supplying a great number of nuclei; and, second, as the number is greater the drops will be smaller, and, on account of their small size, they will have less independent motion, as they will be more guided by the gases than larger drops; there will, therefore, be fewer collisions, and not the same tendency to the diminution of numbers by the coalescence of a number of drops into one. It may be because of the small number of the collisions when the particles are small that electricity has little or no effect on the jet when it is dense from a large supply of nuclei. It is possible that some of the increased density produced by the products of combustion may be due to the slight electrification of gases from flames. But as the electrification from this source is very slight, its effects will be extremely feeble indeed when the dust particles are developed to the size of drops, so that the electricity from this source is not likely to have much effect.

3. *Cold or Low Temperature of the Air.*

We now come to the third cause of the dense form of condensation, namely, low temperature of the air. At first sight it may appear that the above statement contains an already well-known fact. But while in a certain sense this is so, yet there is one point of great importance which, so far as I am aware, has not previously been observed. If we were asked to state what is the effect of the temperature of the air on condensation of the jet, we, probably, would say that when the temperature of the air is high the condensation is very transparent, owing to there being less vapour condensed and to its rapid re-evaporation; and that when the temperature became lower and lower the jet gradually thickens as the temperature falls, owing to the greater amount of condensation caused by the colder air. Such a description is far from a full statement of the facts regarding the changes in appearance with the fall in temperature, and the explanation is correspondingly faulty. There is an influence at work in the condensing jet, which, though due to temperature, is of far more importance than the effect of the temperature on the amount of steam condensed.

When I first encountered this new influence it greatly puzzled me.

I had opened the window of the room where the experiments were being made, and when the fresh air came in, the jet began to behave itself in a most uncertain way. At one moment it was quite steady ordinary condensation, and the next it would conduct itself as if electrically excited. Even after the window was closed it continued to change from the ordinary to the dense form of condensation in a puzzling way. It was first thought that the outer air might be electrified, and tests were accordingly made to see if this were the case. These tests showed that if it were electrified it could be so but slightly, as it did not affect a gold leaf electroscope, which it would require to have done to have produced the increased density observed in the steam jet. Electricity as the solution of the difficulty had, therefore, to be abandoned. The only other influence I could think of as likely to cause the effect was some unknown effect of cold; I, therefore, took the metal tube which had been used in a previous experiment for conveying the products of combustion from the flame to the jet and cooled it. On now presenting one end of this cold tube to the jet it at once responded, and the condensation became as dense as if a flame had been at the other end of the tube, or as if the jet had been electrified.

This effect was all the more surprising since there was no great difference between the temperature of the air in the tube and that of the room, not more than 10° F. Some experiments were, therefore, made to find out the temperature at which this change takes place, and to see if it was as sudden as it appeared to be. The jet was supplied with air cooled in a pipe, which was surrounded with water for regulating the temperature of the air. The steam nozzle was placed just inside one end of the pipe and pointing outwards, so that the jet drew its supply of air out of the tube. No very satisfactory results were got with this apparatus. It may, however, be mentioned that when the air was cooled the jet somewhat suddenly became dense, and again became ordinary when the temperature was slightly raised; but with the apparatus it was difficult to say what the temperature of the air really was when the change took place.

Another method of studying the effect of temperature on the density was tried with fair success; the nozzle was fitted to the end of a horizontal pipe, the nozzle also being pointed horizontally. For this experiment a morning was selected when the temperature of the room was low. When the experiments began the temperature was 40° F. At this temperature the jet was always dense, and neither electrification nor the products of combustion increased its density. The room was now slowly heated, and the jet watched while the temperature rose. Up to a temperature of 46° no change took place, and the jet was not made denser by electricity nor by the products of combustion. But when the temperature rose to 47° the jet began to

show signs of clearing. The clearing did not, however, take place regularly; one moment the jet was dense and the next it was ordinary. These fluctuations would be due to the unequal temperature of the air coming to the jet. At one moment the air would be the air of the temperature of the room; the next it would be this air slightly heated by the metal pipe and nozzle. So that when the jet drew its supply of air horizontally its condensation was ordinary, and when the air currents in the room prevented this heated air from coming to the jet its condensation was dense.

A slight alteration was then made in the arrangement; the jet was now directed downward at the end of the horizontal pipe. By this means the air heated on the pipe and nozzle was prevented from mixing with the jet. The jet was directed at a small angle from the vertical to prevent the hot air and vapour of the jet rising to the nozzle. With this arrangement the following was the result: up to a temperature of 46° the condensation was dense, and neither electricity nor the products of combustion had any effect on the density; but when the temperature rose to about 47° electrification began to have just a perceptible effect in increasing the density. At about 48° the electricity had an easily observed effect, and the products of combustion also had a slight effect. At a temperature of 50° the jet had become decidedly thinner, and both electricity and the products of combustion had a decided effect in increasing its density. When the temperature rose to 55° the jet lost its dense appearance, and both electricity and the products of combustion had a very marked effect.

It might be thought that by observing a steam jet in the open air we could tell if the temperature of the air was above or below a certain point. This, however, can only be done in a very rough way, as the conditions are variable and not within our knowledge. We would require to know the pressure of the steam, and the degree to which the air was heated by the pipe. In a general way it may be stated that in the open air a steam jet looks dense if the temperature be below 50°, and ordinary if above 55°. But it is often difficult to say what is ordinary and what is dense condensation, unless the observations are made carefully and by examining how close to the nozzle the particles are visible. Of course if we could electrify the jet, or supply it with the products of combustion, we could tell whenever the temperature was over or under 47°.

The sudden alteration in the appearance of the jet when supplied with air at a temperature of 46° points to some change in the influences in action in the condensing jet. The great increase in density cannot be due to an increase in the amount of vapour condensed, as the fall in the temperature is slight. Further, it will be observed that the jet has ceased to be influenced by electricity, and by the products of combustion. The only explanation I could think of was, that at

the temperature of the mixed cold air and steam some alteration had taken place in the surface films of the water drops. The jet looked as if something came into action at that temperature which prevented the drops coalescing when they came into collision, or, what would amount to the same thing, that at high temperatures there was no tendency for the drops to recoil after impact, and that when the temperature fell this property made its appearance, and prevented contact in the same way as we have supposed the electrification does.

The simplest way of testing this explanation was to repeat Lord Rayleigh's experiment with water jets, but in place of cold water using hot. The result is, the experiment entirely confirms this explanation. So long as the water in the jet is above a certain temperature there is no scattering whatever, but perfect coalescence of the drops on contact. As a consequence the jet is not influenced in the slightest degree by the presence of an electrified body. It is only after the temperature falls below a certain point that the scattering commences, and electricity begins to have an influence.

This experiment shows that it is only when the drops are below a certain temperature that their surface films act in the way we are accustomed to observe at ordinary temperatures, that is, repel each other; and that when the temperature is high there is an entire change, and the surface films no longer repel, but coalescence of the drops takes place at each collision. It will be noticed that the point here is, not the appearance of any new influence with the low temperature, as the films are then in the condition with which we are acquainted; it is at the high temperature that the new condition comes into action, and the films lose the resisting action with which we are acquainted.

Now it seems extremely probable that the change in the appearance of the steam jet when the temperature of the air is lowered is due to the temperature of the jet falling to the temperature at which this repulsive action makes its appearance.

There is, however, an experimental link wanting to bind these two phenomena together, which I have desired to complete, but unfortunately experimental difficulties stop the way. The link wanting is some experimental proof that the jet gets dense at the same temperature that the water jet begins to scatter. On attempting to take the temperature of the jet difficulties presented themselves. If it is to be taken with a thermometer, where is it to be placed? A very slight change in the position of the bulb of a thermometer placed in the jet gives a different reading. It does not matter whether the change be made nearer or further from the centre of the jet, or nearer or further from the nozzle: in all cases a very slight change gives a considerable difference of temperature. It may, however, be stated that when the bulb was placed in the centre of the jet, and

near the nozzle, it showed a temperature of about 130°, but that figure can only be looked upon as a very rough approximation to the true temperature.

One or two attempts were, however, made to find the temperature at which water films cease to have any repulsive action. This was done by means of a small water jet; and it was found that above 155° there was no scattering. It was not till the temperature fell below that point that electrification had any effect. This was the temperature of the drops themselves, not of the supply for the jet; and it may not be quite accurate, as the drops tend to cool very quickly. Another method of finding this temperature was to observe the highest temperature at which the mist drops floated on water, in the experiment previously described. This method is not very satisfactory, on account of the difficulty of seeing the drops when the temperature is high, owing to the amount of condensed steam hanging over the water. It is also difficult to keep the surface of the water clean. The tests by this method gave a temperature considerably higher than that given by the water jet. Neither of these methods, however, promises to give satisfactory information on this point; but, if it were desired, the effect of temperature on the contact of films could be studied in a more accurate way.

It is difficult to imagine any sudden change in the action of the films at or about the temperatures indicated. There is no corresponding change, so far as I am aware, in the surface tension. We might picture to ourselves the change to be brought about by the alteration which takes place in the intervening gases. When the drops are cold, the bounding surfaces are water and air with very little vapour in it. And perhaps we may be permitted to assume that the surface-film has a layer of air condensed on it, and it may be this condensed layer of air which prevents contact when the drops come into collision. But when the temperature is high, the conditions are changed. The bounding surfaces are now water and air with a large amount of vapour in it, and this vapour may play an important part in bringing about the contact, by the violent interchange of water molecules taking place at the surfaces of the films, and weakening the condensed films of air. If this explanation be correct, then there is really no sudden change in the action of the films, and the repulsion is a gradually increasing one with fall of temperature. Though the somewhat sudden change in the appearance of this jet might seem to indicate a sudden change in the action of the films, yet the change may be really a slowly increasing one, and the sudden change in the appearance of the jet may be due to the repulsion rising to such an amount that the very small particles are prevented from coalescing. If the relative temperatures given for the coalescence of water drops and mist drops be correct; then the

gradual rise in the repulsion with fall in temperature may be the explanation of why the drops in a water jet coalesce at a lower temperature than the mist drops on the surface of water. The water may require to be cooled to a lower temperature before the repulsion is sufficient to prevent the heavier drops from coalescing, while the less repulsion at the higher temperature may be sufficient to prevent the lighter mist drops from coming into contact. The same explanation helps to account for the increased density produced by increasing the dust particles, a less repulsion being sufficient to protect the excessively small drops.

The explanations we have here offered of the action of electricity and low temperature are in complete agreement. In ordinary condensation when the temperature of the air is high there is no surface repulsion, owing to the high temperature in the jet, and many of the particles coalesce on collision with each other; but, when the drops are electrified, their mutual repulsions prevent contact, and the result is a large increase in the number of drops and a dense form of condensation. On the other hand, when the temperature is lowered, surface film repulsion comes into action, contact is prevented, and the drops do not coalesce on collision, and the result is exactly the same as if they were electrified.

In these remarks no reference has been made to the effect of the dryness of the air on the density of the condensation. It seems probable that the relative humidity of the air will have a less influence on the density than on the duration of the jet, that is, the length of time the drops take to evaporate.

4. *High Pressure of the Steam.*

The fourth cause of the dense form of condensation is high pressure of the steam. If the temperature be below 46° the condensation is dense at all pressures, but as the temperature rises, the condensation ceases to be dense if the pressure of the steam be low. But if we now raise the pressure, the jet again becomes dense, and the higher the temperature of the air the higher the pressure must be raised to produce the dense form of condensation. The action of the high pressure in producing the dense condensation is more complex than any of the previous causes. It acts, first, by the more rapid movements of the jet mixing a larger amount of air with the steam, by which means a greater number of dust nuclei are taken into the jet; and, second, a lower temperature is also produced, which probably brings the temperature of the drops low enough for the repulsive action of the films to come into play. But in addition to the effects of a greater amount of air being mixed with the steam, a third action here comes into play. Owing to the violent rush of steam, the con-

densation takes place more rapidly; and it has been found that, the more rapidly the condensation is effected, the greater is the number of particles formed. If the condensation take place slowly, a much less number of nuclei are sufficient to relieve the supersaturation, as there is time for the movements of the water molecules to take place; but if the rate of condensation be forced, then the tension of supersaturation compels a great many more dust particles to become centres of condensation. The result of this is, that with two samples of the same mixture of air and steam, if one of them be condensed slowly, the clouding is thin, while if the other be condensed quickly, it is thick. This action will come into play in the steam issuing at high pressure, when the steam is rapidly expanded, cooled, and then mixed with cold air.

The increased density produced by increase of pressure also takes place somewhat suddenly, though not quite so suddenly as when the density is produced by the other causes. The jet first gradually thickens as the pressure rises, then a stage is arrived at when it somewhat suddenly becomes dense. When this last stage is arrived at, neither electrification nor the products of combustion cause any increase in the density. The first thickening is probably the result of the quickening of the condensation and increase in the number of dust nuclei; and the sudden increase in density is probably due to the temperature falling low enough for the films of the drops to have a repulsive action, sufficient to prevent them coalescing.

5. *Rough Nozzles and Obstructions in front of Jets.*

If we use a nozzle of irregular form, or having roughened edges, it is found that it gives a dense condensation at a lower pressure than a nozzle of circular section with smooth bore and thin even edges. This is owing to the irregularities in the nozzle producing eddies in the jet, and mixing a greater amount of air with the steam, so cooling it more and supplying it with a greater number of nuclei. It, in fact, acts in the same direction as increase of pressure, and aids pressure in producing its results with a less velocity of steam.

An obstruction in front of the jet acts in a similar manner, if we have a jet of steam of such a pressure that at the temperature of the air it gives only the ordinary form of condensation. If now we place an obstruction in front of the jet so as to produce eddies, the condensation at once becomes dense. Wind has also a somewhat similar effect. The reason of the increased density in these cases is the same as for the jets issuing from irregular nozzles. They all assist the pressure in intensifying the density of the condensation, by lowering the temperature of the jet, increasing the number of nuclei, and quickening the rate of condensation.

The Seat of the Sensitiveness of the Jet.

The seat of maximum sensitiveness to all influences tending to change the condensation from ordinary to dense is near the origin of the jet close to the nozzle. The different influences, however, affect the jet to different distances from its origin. The most limited in the range of its action is cold, which only produces the dense condensation when it acts near the nozzle, whereas some of the other influences have some effect, though a gradually decreasing one, to a distance of 2 or 3 cm. from the nozzle.

The following experiment illustrates the limited range of the action of cold:—A piece of ice about 2 cm. thick was selected, and a small hole bored through it. The ice was then held so that the steam jet passed through the opening. While the ice was held at a distance of 1 cm. from the nozzle, almost no effect was produced, though much cold air from the ice was mixing with the jet. But when the ice was brought nearer the origin of the jet, so that the nozzle almost entered the plane of the ice, the dense condensation immediately appeared.

The range of sensitiveness of the jet to change of condensation by obstructions is also very limited. It is only when the obstruction acts near the nozzle that its effect is great. For instance, the blade of a knife resting on the nozzle, with its back or edge pointing in the direction of the jet, and depressed so as to deflect the jet slightly, causes the jet to become very dense. But if the knife acts on the jet at a distance of only 1 cm. from the nozzle, very little increase in density is produced.

The range of action of electricity is much greater than that of cold or obstructions. If we screen the nozzle and the part of the jet near it from electrification, it will be found that at a distance of 3 or 4 cm. a slight increase in density can be produced with the electrification used in these experiments.

The action of the products of combustion has a range similar to that of electricity. If the products are supplied to the jet at a distance of 3 or 4 cm. from the nozzle, a slight increase in thickness can be detected where the impure gases meet the jet; but the effect is very slight compared with that produced when the gases are taken in at the origin of the jet.

The limited range of the action of cold is quite what might be expected. Near the nozzle the temperature of the jet is high, and there the drops have no repulsive action; but at a short distance from the nozzle the temperature is low enough to allow this repulsion to come into action, and the consequence is that any further cooling after the temperature is below a certain point produces little or no effect. It is only when the temperature is above this point that

the cooling has any influence. The same explanation holds good for the limited range of the action of obstructions in front of the jet.

At a distance of a few centimetres from the nozzle new drops seem still to be forming, as the density of the condensation is slightly increased by increasing the supply of nuclei at that distance. The drops seem also occasionally to coalesce at a distance of 3 or 4 cm. from the nozzle, as electricity slightly increases the density of the condensation even at that distance.

Part II.

Colour Phenomena connected with Cloudy Condensation.

In the following remarks it is not intended to discuss the many colour phenomena which are known to be connected with cloudy condensation. Attention will be confined principally to some new phenomena, the experimental illustration of which has been developed in the present investigation.

Before describing these experiments, it may be as well to refer to some changes which take place in the constitution of cloudy condensation, both while it is forming and after it has been developed, as it will be necessary for us to keep certain points in view while discussing the colour phenomena. There are two points to which special reference is required. These are, first, the manner in which the appearance of the condensation is affected by the greater or less degree of supersaturation, that is, by the rate at which the condensation is made to take place; and, second, the changes which take place in the appearance of this cloudy condensation after the tendency for the vapour to deposit has stopped.

These two points may be best discussed by taking the second first. Suppose we blow some steam into the air inside a glass vessel, and leave it undisturbed; if we examine the cloudy condensation after a time, we shall find that a considerable change has taken place in its appearance. The change is due to two causes: part is due to the gradual descent of the particles by which a clear space is formed in the upper part of the vessel. But it will also be observed that the clouding in the lower part is much thinner than it was at first. Probably part of this thinning is due to some of the particles having fallen to the bottom of the vessel, but this is not the principal cause of the change. The thinning is due mainly to a reduction in the number of particles in the air, by the smaller particles gradually becoming absorbed by the larger ones. This is caused by the vapour-pressure at the surface of small particles being greater than at the surface of larger ones, with the result that the smaller particles evaporate in air of the same humidity in which the larger ones are condensing vapour.

We are now in a position to understand our first point, namely, why the degree of supersaturation by which the condensation is produced should have an effect on the appearance of the condensed vapour. For the study of this point the condensation produced by expansion is the most convenient, as it is more under our control than the condensation in steam jets. Suppose we take a glass flask connected with an air-pump. If we wet the inside of the flask and then fill it with unfiltered air, the slightest expansion of the moist air by the pump will cause condensation to take place. But the density of the condensation which can be produced by any degree of expansion will depend on the rate at which the expansion is made. If the expansion be made very slowly, the clouding is very thin; but, if it be made rapidly, it is very thick. If the expansion be done slowly, the amount of supersaturation is only slight, and only the largest dust particles come into action as active centres of condensation; and after a particle of dust has once become a nucleus, it has then, in virtue of its size, an advantage over the particles which have not begun to have vapour condensed on them. The result of this is that, so long as the degree of supersaturation is very slight, these large particles relieve the tension, and if by any chance other dust particles become active, any reduction in the rate of condensation allows the large particles, after they have relieved the tension, to rob the small ones of their burden of water, so that a slow rate of condensation always produces a small number of drops and a thin form of clouding.

But now suppose you cause the expansion to be made rapidly; the supersaturation then becomes much greater, as there is not time for the water molecules to select a resting place, and the small number of large dust particles cannot relieve the tension, and the result is a much greater number of nuclei are forced into action. And all these nuclei continue to grow so long as the supersaturation is kept up, but the larger ones grow most. After the tendency to condense has begun to diminish, those particles which have accumulated least are the first to feel the change, and cease to grow, while the larger ones are still accumulating. But after the tendency to condensation has ceased altogether, the changes in the clouded air are not at an end. The smaller drops begin to lose their accumulated moisture, while the larger ones are still growing—growing at the expense of the gradually diminishing smaller ones. This process goes on till most of the small ones have lost all their burden of water, which has been absorbed by the overgrown larger ones; and in the end a comparatively small number of drops have absorbed the moisture which was previously distributed over a vast number of particles. The larger particles have, so to speak, eaten up the smaller ones. How like the above looks to a page in the "struggle for existence" in the animal or vegetable world!

Colour Phenomena in Steam Jets.

Steam escaping into the atmosphere has been observed on a few occasions to have the power of absorbing certain of the rays of light, and causing the sun, when seen through it, to look "blue" or "green." Principal Forbes observed colours in the steam escaping from a safety valve. Mr. Lockyer* states that, when on Windermere, he saw the sun of a vivid green, through the steam of a little paddle-boat. I believe a few others have seen this phenomenon under similar conditions, but so far as I am aware no one has followed out the suggestion, and investigated the manner in which the colour is produced.

Mr. Bidwell, in his experiments on the electrification of steam jets, studied the action of the jet on light, by casting the shadow of the jet on a white screen, using for illumination the lime light. He found that the shadow of the ordinary jet—that is, the light transmitted by the jet—was nearly colourless, but that when it was electrified the shadow became of a dark orange-brown colour.

The colour of the "green sun" seen through steam has been attributed to the absorption of both ends of the spectrum by the aqueous vapour. This explanation is obviously not the correct one, as it will be found that a moderate length of steam has no perceptible selective absorption. Through a length of even one metre of steam, white objects are not coloured, and we shall presently see that the colouring depends not on the vapour, but on some action of the small drops of water in the condensing steam.

For the purpose of studying the colour phenomena of steam jets I have found it to be a great advantage to surround the jet by solid walls. When a jet condenses under ordinary conditions, the constitution of the jet rapidly changes in its passage away from the nozzle, owing to the air mixing with it; and it has been found that by enclosing the jet in a tube, after a certain amount of air has been mixed with the steam, that the conditions can be kept fairly constant for some length of time, and the colour phenomena taking place can, therefore, be more easily studied under these conditions. The tube used for this purpose need not be of any special size. For a jet from a nozzle of 1 mm. bore a tube of 7 or 8 cm. diameter, and about half a metre long, does very well, but a smaller and shorter tube may be used. With the larger size of tube it may be necessary to check the current through it. This is best done by placing a piece of glass near the exit end of the tube, the opening between the glass and the end of the tube being regulated to the required amount by observation. When a small jet of steam is used with the large tube

* 'Nature,' vol. 18, p. 155.

open at both ends too much air is drawn in, and the effect is much the same as if no tube were used. The end of the tube has, therefore, to be closed to a certain extent, to produce the colour phenomena. But when high pressed steam is used, no check on the circulation through the tube is necessary. The steam nozzle should be placed outside the tube and a little to one side, so that the eye can be brought into a line with the axis of the tube and a clear field of view obtained while the jet plays into the open end of the tube. This is an experiment which well repays the trouble of making it. When the amount of steam, dust, and other conditions are properly proportioned, the colours seen are very beautiful. With ordinary condensation the colour varies from a fine green to lovely blues of different depths. The pale blues equal any sky blue, while the deeper blues are finer than the dark blues seen in the sky, as they have none of the cold hardness of the dark sky blues, but have a peculiar softness and fulness of colour.

Suppose now the tube is fitted up pointing to a clouded sky, or other source of light, and that the steam jet, under slight pressure, is blowing through it. If the exit end of the tube be open, we shall see very little colour, and what is seen is only near the origin of the jet. If now we partially close the end of the tube with the glass plate, to prevent the jet drawing in so much air, we shall find that colour begins to appear, and that when the plate is properly adjusted the tube looks as if filled with a transparent coloured gas. The first decided colour to appear is generally green, though I think I have frequently seen a pale crimson before the green was visible. If the circulation be checked still further, the colour will change to blue of a greater or less depth according to the conditions.

The above are the effects which may be looked for when the condensation of the jet is ordinary; but suppose it be now caused to change to the dense form, then the colour seen through the tube also changes. If, when the jet is condensing in the ordinary way, and the transmitted light is green, we cause the condensation to change to dense, then the colour also changes and becomes deep blue, or, if the ordinary condensation gave blue, the colour changes, when the jet is dense, to a dark yellowish-brown. But between the blue and the yellow there is always an intermediate stage when all colour disappears and the light is simply very much darkened. The most common effect of the change of the condensation from ordinary to dense is for the transmitted light to change from blue to a yellowish colour, and it does not matter how the change in the condensation is effected; the colour always changes in the same way. We can, therefore, cause the colour in the tube to change by electrifying the jet, by a supply of cold air, by a supply of the products of combustion, by increasing the pressure of the steam, and by placing an ob-

struction in front of the nozzle. When any of these, either separately or combined, comes into action, the change is always in the same direction, and if the colour was blue, it changes to yellow.

It may be as well to note here that the yellows produced by most dense forms of condensation are far from fine, and cannot be compared with the blues. The yellows are not at all unlike the colours occasionally seen through smoke, or in a thunder cloud. Though this is the case with the dense condensation produced by most of the causes, yet a very fine yellow is obtained when high-pressed steam is used.

It has been suggested that, because an electrified jet causes the light transmitted through it to be coloured of a dark yellow-brown, and as the colour seen in thunder clouds is similar, that, therefore, the lurid colour of thunder clouds is due to the electrification. From what is stated above, it will be seen that electricity is only one of a number of influences which can change the condensation of the steam jet and make the light transmitted through it of a yellow-brown colour. Further, there is no evidence to show that electricity has any influence of this nature on the form of condensation taking place in clouds, and we are hardly entitled to expect it to have any such influence, as the conditions under which the steam condenses in a jet are very different from those under which condensation takes place in clouds; and we have seen that electricity has no effect on the nature of the condensation when it takes place in a mixture of hot moist air and cold air. There is still another fact which points to the same conclusion. If, in the steam jet, the proportions of dust, pressure, &c., are such as to give an earlier stage than the blue, suppose the transmitted light be green, then the electrification may not change it to yellow, but may only make it blue. At present, it is therefore very doubtful whether the electricity in a thunder cloud has anything to do with its colour.

Colours observed in Cloudy Condensation produced by Expansion.

Though previous experiments had made me well acquainted with certain colour phenomena, seen when cloudy condensation is produced by the expansion of moist air in a receiver, yet I had never observed any colours in the light transmitted directly through the clouded air, such as are seen in the jet of steam when enclosed in a tube. It seemed extremely probable that the reason for this would be, that when the condensation is produced by expansion, the process is slow, and the particles will, therefore, be too few to produce any colour effects. In a steam jet, the expansion, cooling, and condensation take place very rapidly, and for that reason the number of water particles formed is very great. An experiment was therefore

arranged, in which the air could be very rapidly expanded, so as to produce a high degree of supersaturation, which it was hoped would cause a great number of dust nuclei to become active. To test this idea, all that was necessary was that the receiver used for holding the moist air should be much smaller than usual in comparison with the capacity of the pump, and that the light be transmitted through some length of air. The plan adopted was to use an air-pump of ordinary dimensions, and for a receiver, a metal tube closed with glass ends. The first apparatus prepared for this experiment was found to give satisfactory results, and the alterations since made have not been of any great advantage.

The apparatus consists of a brass tube 2·3 cm. diameter and about half a metre long. It is provided with glass ends, fitted on air-tight, and is provided with a branch pipe at each end. One of these branch pipes is connected with an air-pump, and the other has a stopcock fixed to it. This stopcock is connected with a pipe for bringing to the tube the air to be experimented with. If the tube be mounted horizontally, the particles rapidly fall and the phenomenon is visible for only a short time. The tube is, therefore, best mounted vertically, and with a mirror placed at the lower end of the tube to reflect the sky or other source of light up through the tube to the eye of the observer.

The air-pump used is a single cylinder instrument of 3·17 cm. diameter and 19·3 cm. stroke, so that its capacity is about three-quarters that of the tube receiver. If we take the instrument outside the house and make one or two strokes of the pump to fill the receiver with air of the place, then close the stopcock, and make a rapid stroke with the pump, little effect is produced on the light transmitted through the tube. But if we take the instrument into a room where gas has been burning, so that the air is full of dust particles, and repeat the experiment, very beautiful colours are seen on looking through the tube when the air is expanded. Or, better still, if we collect the gases rising from a small flame and draw them into the tube, the result is a display of an exceedingly lovely series of colours, full, deep, and soft, in some respects reminding one of polarisation colours. As in the steam jet, the blues are the finest, and the tube looks, at times, as if filled with a solution of Prussian blue. The colours produced in this way are more uniform and equal in all parts than those seen in the steam jet, unless when the jet is very carefully adjusted; the yellows are also much finer, and the colours more varied than those seen in the steam jet.

There is, however, one most disappointing thing connected with these colours produced by expansion: they are very fleeting. Their full beauty lasts but a second or two, and they soon fade away, the colour growing dimmer and feebler every moment. This is owing to

the differentiation which takes place in the particles forming the cloudy condensation. As has been already explained, the small drops rapidly diminish in size while the large ones increase, and as in these experiments the drops are very close to each other, these changes take place the more rapidly. These changes are also taking place in the steam jet, but, owing to the constant supply of new drops, the older ones are swept away before the change is observed. The following experiment will, however, show that these changes are taking place in the steam jet also. If, while the jet is condensing dense and the transmitted light is yellow, we imprison some of the jet by closing both ends of the tube, we shall find in an extremely short time that the colour will change to blue, after which it will fade as the drops increase still further in size, and fall. In this experiment we have a proof of the statement that when the jet is electrified the drops are smaller than when not electrified, and not larger, as has been supposed; as this experiment shows, if we begin with drops transmitting yellow light, that as the drops diminish in numbers and increase in size, the transmitted light changes to blue.

The conditions of the experiments for producing colour by cloudy condensation, produced by expansion, have been varied in a number of ways. After the air has been cooled by the expansion, the layer of cloudy air in contact with the walls of the tube rapidly acquires heat from the metal, and the rise in temperature quickly evaporates the cloudy particles and causes a clear space all round next the walls, so limiting the colour to the centre of the tube. The receiver was therefore increased in diameter to get rid of the disturbing effects of the heating of the air on the walls of the tube, so as to have a larger mass of air beyond this influence; but no decided advantage has been obtained. It was afterwards found that the difficulty of studying these colour effects in small tubes can be easily overcome by wetting the inside of the tube. With this precaution the air next the walls is kept saturated and the temperature of the walls is lowered by the heat given off to evaporate the water, with the result that the colour is the same all over the field and close up to the walls.

Large tubes might be used for showing these colour phenomena to an audience, a parallel beam of light being sent through them, which would become coloured when the dusty air in them was expanded. One large tube tried has a diameter of 7 cm., and is 50 cm. long. With a receiver of that capacity it would be hopeless to attempt to produce any colour effects with an ordinary air-pump alone; a vacuum receiver has, therefore, been added to the apparatus. This receiver is made of metal; it is 15 cm. diameter and 60 cm. long, with round ends. There are two tubes attached to it, one for connecting it with the air-pump, and the other is provided with a stopcock, to which a tube is attached,

by which it is connected with the experimental receiver. The stopcock is closed, and the pump worked till most of the air is taken out of the receiver; and when it is desired to expand the air in the experimental tube the stopcock is opened, when a violent rush of air takes place, and the pressure is rapidly lowered in the experimental receiver, and a dense colour-producing form of clouding is produced.

The Conditions causing the Different Colours.

For studying the conditions which give rise to the different colours seen in these tubes, the air-pump and the small tube will be found to be the most suitable. Supposing these to be fitted up, the following will show how the colours change with the conditions :—

First, the effect of the degree of saturation of the air. If the air be dry the colours are not good, and some degree of expansion requires to be made before any effect whatever is produced on the air; and when the colours do appear, it is only in the centre of the tube that they are seen, the space all round next the walls being free from condensed particles. As the humidity is increased, this unclouded space near the sides of the tube gradually diminishes. The colours are, therefore, best studied when the air is saturated and the inside of the tube wet. When this is done the colours extend to the walls, and completely fill the tube.

Second, the effect of the number of dust particles in the air. If we use ordinary outside air, the colours are very faint or invisible. Suppose some slight colour is visible, then it will be found that a very slight expansion, say one-fifth of a stroke of the pump, will give a pale blue, and if the expansion be increased the colour will change. If, now, we use air from a room where gas is burning, and fill the tube with it, we shall now, on expansion, get a much deeper blue, and it will be observed that a greater expansion must now be made to get the best blue, and before the colour begins to change. If we alter the conditions still further, and fill the tube with air in which is mixed a good deal of the products of combustion, we shall find that the condensation is now so dense that we can scarcely see through the tube; but it will be noticed that the colour is a very deep blue, and that a full stroke of the pump was necessary to produce this deep blue, but in this case no change of colour was produced with that large degree of expansion.

These experiments show that, with few dust particles, a slight expansion will produce the best blue, and that, as the number of particles increases, the amount of expansion necessary to produce the best blue also requires to be increased, the depth of colour increasing with the increase in the number of dust particles. The explanation of the differences here is very simple. With few particles a very

slight expansion will deposit enough moisture to make the small number of drops of the size sufficient to give the best blue colour; but, as the number of particles is increased, more moisture must be deposited before the increased number of drops are made large enough to give a full blue; hence with a larger number of particles a greater expansion is necessary to produce this effect.

Third, the effect of the size of the condensed particles. As has been stated, a slight expansion produces a blue colour if the number of particles be small, and if the expansion be increased after the blue is produced, the colour changes; and we shall now describe the successive colours which appear as the degree of expansion is increased, that is, as the size of the water particles is increased. When the expansion begins, blue is the first distinct colour to appear, but very pale yellow and slightly reddish colours have been noticed before the expansion was sufficient to produce the blue. These reddish colours can be seen very distinctly when we use an excessively great number of particles, and they are best seen with gas light. These reddish colours imperceptibly change into blue as the expansion is increased, and the blue in turn changes by minute degrees into green with further expansion, and the green in turn changes to yellow; then a brownish colour appears, which changes to a somewhat mixed purple; then the blue returns again, to be followed by green and yellow, as the expansion is still further increased. It is not easy to get this sequence of colours carried so far. Sometimes one stroke of the pump only carries the colour on to yellow; sometimes it may go to the second blue or green, but less frequently to the second yellow. The final colour depends on the number of particles present. It is necessary to have a good many drops, so that the colour may be distinct, and yet not too many, or the expansion may not be sufficient to grow the particles large enough to give the second series of colours. It is found that a high expansion, produced by two or more strokes of the pump, does not give satisfactory results.

We have seen that by increasing the number of dust particles the depth of colour was increased; it therefore seemed possible that these colour phenomena might be made visible in even a short column of air, and that they might be shown by means of ordinary glass flasks. The following experiment was, therefore, arranged:—A flask, about 18 cm. diameter, was fitted with an india-rubber stopper, through which passed two tubes. One tube was connected with the metal vacuum receiver already described, the other had a stopcock attached to it. The stopcock was connected with a long metal pipe, which led to a wide tube placed over a small flame. Air charged with the products of combustion was drawn into the flask through this pipe; when sufficient impure air was drawn into the flask, the stopcock

was closed; when the air in the flask was now suddenly expanded, it looked as if it had been filled with a transparent blue gas. The colour, when held against a white cloud, was almost exactly the same as that of the blue sky. The colour in the flask faded rapidly, as in the experiments with the tube. The particles being very closely packed in most of these experiments, the subsequent change is all the more rapid.

Effect of Temperature.

To observe the effect of temperature on these colour phenomena, another tube was prepared, with glass ends, and jacketed, so that the air in it might be heated or cooled to any desired temperature. The result was very much what might have been expected: at the different temperatures all the colours made their appearance in the usual order, but there was a considerable difference in the amount of expansion required to produce a given colour with change of temperature. At a high temperature each of the colours appeared with a less expansion than when the temperature was low. In making these tests the number of dust particles in the air must be kept as constant as possible. For this purpose windows and doors should be kept closed for some time before beginning, and the experiments should be repeated without change of conditions. When the air was cooled to about 35°, it took two strokes of the pump to develop a full blue, and three strokes made it only green. At a temperature a little over 50°, two strokes made it green, while if the air was heated to about 80°, two strokes sent it past blue and green and on to yellow, and less than one stroke made it full blue. These differences are due to more vapour being present and being condensed, with the same amount of expansion, when the air is hot than when it is cold. It should be stated that in all cases the air was saturated, the inside of the tube being wet.

The tube was also cooled down to 6° F., but no difference was observed in the nature of the phenomena. The particles at that temperature seemed to be still in the liquid form.

Light Transmitted.

The light transmitted directly through the cloudy condensation has been examined by means of a small spectroscope. One of the tubes was mounted vertically, and a mirror placed at the lower end; the spectroscope was temporarily mounted over the upper end of the tube; a small mirror was placed between the spectroscope and the glass end of the tube. This small mirror covered half the field of the spectroscope, and reflected light from the same source as that reflected by the mirror at the lower end of the tube, so that one-half of the field

gave the spectrum of the light, and the other half the light after passing through the cloudy condensation. The conditions in the experiment are too fleeting for satisfactory observation. The only thing noticed was a darkening of the whole spectrum, with a greater absorption at certain points than at others. When the light was blue, in addition to the general reduction in brightness, the red end was more reduced than any other part, and there was also a very marked shortening of the spectrum at this end. When the colour was yellow, the reverse was the case. The blue was almost entirely cut out, while the yellow was far the brightest part of the spectrum.

An examination has also been made of the diffraction colours as seen in the halos surrounding bright lights. The most convenient way tried of observing these colours was to use an ordinary glass flask of 18 cm. diameter, connected with the metal vacuum receiver, as already described. For the source of light gas may be used, but a better result is obtained with the light of the sky. In order to observe these colours easily, the window should be closed, all but a narrow vertical strip; and it improves matters to have all surfaces on each side of the opening painted black. When the air in the flask is expanded, the vertical bands of diffraction colours are distinctly seen on each side of the bright light. If now we keep the amount of dust in the air constant during the experiments, we shall find, that on opening the stopcock to the vacuum receiver very slowly, we will get the usual cloudy condensation, and that the diffraction colours will be quite distinct. But if we repeat the experiment, and this time open the stopcock very suddenly, so as to cause a rapid expansion, the colours will be found to be very much improved, being far more brilliant. This is due partly to the greater number of particles engaged in producing the effect, but chiefly to the much more equal size of the particles when they are suddenly developed than when slowly grown.

It is found that we must not have too many particles present, or the diffraction colours will not be good; their size does not seem to be great enough to produce the phenomena. If, for instance, in place of using the air of the room, we take into the flask air coming from a small flame, the colour phenomena in the flask all change: when there were few particles the light transmitted directly through them has so little colour it is not noticed, while the diffraction colours are fine; but with many particles the direct light becomes coloured, while the diffraction colours are softened and have lost much of their brilliancy. When the particles are sufficiently numerous to cause the directly transmitted light to be of a thin blue, the diffraction colour next the blue light is nearly the complementary yellow, and this yellow light extends to near the limits of the flask. If more particles be added, the colour of the transmitted light becomes deeper blue, but it

is difficult now to say what the diffraction colours are. The convection currents in the flask now make themselves visible; the air on each side of the blue direct light is suffused with a variety of colours, not now in regular vertical bands, but irregularly distributed and in movement through the flask.

Cause of the Colour.

These experiments show that the colour produced by the small drops of water depends on the size of the drops, and the depth of colour on their number. But it is not so easy to follow the manner in which the drops produce the colour. If we take the simplest case, we can easily see how part at least of the colour is produced. In the steam jet condensing dense, and colouring the transmitted light yellow, part of the effect is no doubt due to some of the particles in that form of condensation being so small that they reflect and scatter the shorter waves of light, while they allow the longer ones to pass through. The colour in this case is partly caused in the same way as the yellow produced by small particles suspended in liquids, as in Brücke's experiment with mastic, or as when silver chloride is formed from a solution of the nitrate. The light reflected by the liquids in these experiments is of a bluish tint, complementary to the yellow light transmitted by them, and this blue light is polarised. It has been found that when the steam jet is of a good yellow by transmitted light, it reflects a good deal of a bluish light; and further, this blue light is polarised in the same way as the light from the small particles in the experiments with liquids.

While this explanation helps us so far to understand the manner in which the yellow light is produced in steam jets, yet it fails to explain the succession of colours seen in the expansion experiments, where blue first appears, then green and yellow; and when the expansion is still further increased, the blue again returns to give place to a second green and yellow. The most probable explanation of these colour phenomena is that they are produced in the same way as the colours in plates, somewhat after the manner Newton thought the colour of the sky was produced. The order of succession of the colours in thin plates is the same as in these condensation phenomena. As no white follows the first blue, it seems probable that the first spectrum, or order of colours, is not observed; that the two generally seen are the second and third.

Some experiments were made with a glass tube receiver, in place of the metal one, to see if there were any coloured light reflected in these expansion experiments of the same kind as is seen under certain conditions in the steam jet; but no such colours have been observed. It is possible they may be present; but, owing to the great amount of

white light reflected by the larger particles, any coloured reflected light that may be present is masked.

Green Sun.

On a few occasions the sun has been observed to be of a decidedly greenish colour, while on other occasions it has appeared blue. The experiments which have been described in this paper seem to offer an explanation of this phenomenon. For a number of days in the beginning of September, 1883, the sun was seen of a decidedly blue or green colour in India, Trinidad, and other places. Most of the observers who have written on the subject have linked this phenomenon with the eruption of Krakatao, which took place just before the days on which the green or blue sun was seen. From the light thrown on the subject by these experiments, we see that an eruption, such as that of Krakatao, would throw into the atmosphere a supply of the very materials necessary for producing a green sun by means of small drops of water, as it would send into the atmosphere an immense quantity of aqueous vapour and an enormous amount of fine dust—a combination the most favourable possible for producing a great number of minute drops of water.

Professor C. Michie Smith observed the green sun in India, and he says: "The main features of the spectrum taken *on* the sun when green were—

"1. A very strong general absorption in the red end.

"2. A great development of the rain-bands and of all other lines that are ascribed to the presence of water-vapour in the atmosphere."*

It is evident, therefore, that one of the materials necessary for producing this peculiar absorption by means of water-drops was present in an unusual amount in the atmosphere at the time; and it also appears that a fine form of condensation had taken place, as Mr. W. R. Mauley states† that there was at the time a sort of haze all over the sky, and from the letters of different observers this haze seems always to have accompanied the green sun.

One almost wonders that a blue or green sun is not oftener seen, as there are often present all the materials necessary for producing these colours in the atmosphere. On a few occasions I have observed the sun to be of a silvery whiteness, when the vapour in the upper air was beginning to condense, and the sky was covered with a thin, filmy cloud. It is, however, possible that this slightly bluish tint may have been due to the sun being seen more in its natural colour than usual, that is, made much less yellow by our atmosphere than it gene-

* 'Nature,' vol. 30, p. 347.

† *Ibid.*, vol. 28, p. 576.

rally is. There seems to be something preventing the dust and the vapour in our atmosphere acting under ordinary conditions in such a way as to colour the sun blue or green. Perhaps it may be the tendency the particles have to differentiation. This tendency, we have seen from the experiments, rapidly destroys all colour effects, and from this we might suppose it would be impossible that the colours, if produced by water drops, could remain in nature visible for so long a time as they did. But it must be remembered that the particles in the experimental vessels are extremely close together, and the vapour exchanges can therefore take place quickly. If, however, the drops were widely separated, the exchanges would take place slowly. For instance, if the drops in 1 cm. were separated so as to form a column 1 mile long, with a section of 1 sq. cm., we should have the same amount of colour in 17 miles that we had in the 17 cm. of air in the flask, and the particles would be so far apart that differentiation would then take place extremely slowly. But further, if the supply of dust and vapour were constantly kept up by the volcano, the colour phenomena would continue for the same reason that they continue in a steam jet, namely, by the drops being constantly renewed.

A New Instrument for Testing the Amount of Dust in the Air.

As this investigation progressed it became evident that these colour phenomena placed in our hands an easy and simple way of estimating, in a rough way, the number of dust particles in the atmosphere of our rooms, which might be useful for sanitary purposes. An instrument was therefore constructed to see how far the idea could be practically carried out. This new instrument we intend to call a *Koniscope*. In its present form this instrument consists of an air-pump and a metal tube with glass ends, which we shall call the test-tube. The capacity of the pump should be from half to three-quarters the capacity of the test-tube. Near one end of the test-tube is a passage by which it communicates with the air-pump, and near the other end is attached a stopcock for admitting the air to be tested. The test-tube and air-pump may be attached parallel to each other, and held vertically when observing. If this arrangement be adopted, a mirror must be attached to the lower end of the tube. In practice it is found to be more convenient to omit the mirror, and observe with the tube in any position, simply directing it to any suitable light. When this arrangement is used, the pump, for convenience of working, should be attached at right angles to the test-tube. It is found that any want of uniformity in the colour of the field produced by the air heated on the sides of the tube can be greatly obviated by lining the inside of the tube with a non-conducting substance, and

keeping it wet. Blotting-paper is found to do very well, as it holds plenty of water for saturating the air, and is a fair non-conductor. When the inside of the tube is lined with it, the field of colour is fairly uniform, owing to the cooling of the sides by the evaporation when the air enters and when expansion is made.

For illumination, no doubt day light is the best when it can be obtained, as gas light is so deficient in blue rays that colour is not well observed. For convenience of observation, it is found to be best to close the far end of the tube with ground glass, and when working with artificial light ground glass must be used.

I have made a few tests with an instrument of this kind, and find it very easily worked; and for many practical purposes it is sufficiently accurate. It cannot, of course, compare with the dust counter for accuracy; but, on the other hand, it is a much less expensive instrument, and tests can be made far more easily with it, and little special knowledge is required. If we wish to get actual figures for the amounts of dust indicated by this instrument, then it must be graduated by a dust counter. The indications at best, however, will only be very rough approximations to the numbers.

There are three ways in which we might graduate this instrument. We might, for instance, make one full stroke of the pump, and note the colour which appeared. This colour would indicate the number of particles. For instance, if there are few particles, one stroke will make the light first blue, then green, then yellow, and then a second blue and green, and finishing with yellow. But if there are a good many particles present, the same amount of expansion will only make the first series of colours to appear, and if a great many particles are present, the one stroke will not give the whole of the first series of colours, but may stop at the blue. If the temperature of the air were always the same, this method might be adopted, but, as we have seen, an allowance would be required to be made for temperature, as with a high temperature the same degree of expansion carries the colour further up the series.

Another method of graduating might be to note the amount of expansion necessary to give any particular colour, say to give the best blue. With few particles a slight expansion gives the blue, while with many particles a much greater expansion is necessary. But here again the effect of temperature comes in. Temperature observations would therefore require to be taken, and a correction made which it might be difficult to carry out in practice.

At present the best plan of graduating seems to be to note the depth of the blue produced, regardless of the amount of expansion required to give it, and use only this quantity as an index. With few particles the colour is pale, and as the particles increase in number the colour increases in depth. Perhaps some addition might be

made to the instrument for estimating more accurately the depth of colour than can be done mentally. This might be done either by means of coloured glasses of different depths for comparison, or in some other way.

A few comparative observations have been made with the koniscope and the dust counter in the impure air of a room. While the number of particles was counted by means of the dust counter, the depth of blue given by the koniscope was noted. A metal tube was fitted up vertically in the room in such a way that it could be raised to any desired height into the impure air near the ceiling so that supplies of air of different degrees of impurity might be obtained. To produce the impurity, the gas was lit and kept burning during the experiments. The air was drawn down through the pipe by means of the air-pump of the koniscope, and it passed through the measuring apparatus of the dust counter on its way to the koniscope. The indications of the two instruments were taken, and are entered in the following table :—

Dust Counter. Particles per c.c.	Koniscope. Depth of colour.
50,000	Colour just visible.
80,000	Very pale blue.
500,000	Pale blue.
1,500,000	Fine blue.
2,500,000	Deep blue.
4,000,000	Very deep blue.

It is probable that the higher numbers are too low, as the measure of the dust counter has a capacity of only 10 c.mm. With so small a measure it is probable that a good many of the particles are lost.

When making a sanitary inspection, the air outside, or wherever the supply was drawn from, would be tested first, and the depth of colour which it gave would be noted. Any increase from that depth would indicate that the air was being polluted, and the amount of increase in the depth of colour would indicate the amount of increase of pollution. Slight colour can be traced though the number of particles be less than 80,000 per c.c., but the colour is not very decided, the condensation producing principally a darkening effect. It should be noted that the above table refers to a koniscope with a test-tube 50 cm. long. An instrument with a tube 1 metre long would be doubly sensitive, and would show colour with fewer particles.

It is thought that the koniscope will be useful for sanitary inspectors, for investigating questions of ventilation in rooms lighted with gas, and for other purposes. As an illustration of what this instrument can tell us, the following experiment may be given. It shows us how we can trace by means of it the pollution taking place in our

rooms by open flames. The room in which the tests were made is $24 \times 17 \times 13$ feet. The object of the tests was to see if the koniscope could tell us anything definite about the degree of pollution at the different parts of the room, and also about the rate at which it was increasing. For this purpose a small tube was arranged so that one end of it could be raised to the ceiling, or into the air of any part of the room from which it was desired to take the air; the other end of the tube was connected with the koniscope.

The first thing to be done was to examine the air of the room before lighting the gas and beginning the tests. On doing this the air at the level of the observer gave a very faint colour, scarcely perceptible; air drawn from within 3 inches of the ceiling gave equally little colour, and the air inside the room gave the same colour as the air outside. The upper end of the tube connected with the koniscope was then raised to within 3 inches of the ceiling, near one end of the room, and the koniscope left attached to the lower end; three jets of gas were now lit in the centre of the room, and observations at once begun with the koniscope. Within thirty-five seconds of striking the match to light the gas the products of combustion had extended to the end of the room; this was indicated by the colour in the koniscope suddenly becoming of a deep blue. In four minutes the deep blue-producing air was got at a distance of 2 feet from the ceiling. In ten minutes there was strong evidence of the pollution all through the room. It was strongly indicated near the windows, owing to the down current of cold air on the glass. This impure down current could be traced to the floor, and onwards to the fireplace; while a pure current could be traced from the door to the fireplace. In thirty minutes the impurity at 9 feet from the floor was very great, the colour being a deep blue.

The wide range of the indications of the koniscope, from pure white to nearly black-blue, makes the estimates of the impurity very easily taken with it; and, as there are few parts to get out of order, it is hoped it may come into general use for sanitary work.

The few experiments I have made with this instrument have clearly pointed out that a window is not an unalloyed blessing as regards the purity of the air in our rooms, however much we may have been in the habit of thinking otherwise. In all cases it has been found that in rooms where gas is burning the air near the window is very impure. This impure down current of air near the window has been traced by the koniscope in all rooms tested. The impurity is caused by the cold air on the window sinking, and drawing down the impure air near the ceiling, and this impure air is mixed with the lower air which we are breathing. This effect is, of course, greatest when the windows are unprotected by blinds, shutters, or curtains. It is evident that though a window may supply pure air when it is open,

it yet does much harm when closed, by bringing down the impure air, which, if undisturbed, would have a less injurious effect.

It is to be regretted that this investigation does not promise to yield much of practical value; nevertheless, as we cultivate not only fruits but flowers, so, for the same reason that we cultivate the latter, it is thought that these experiments will repay the attention of physicists. The colours produced by such simple materials as a little dust and a little vapour are as beautiful as anything seen in nature, and well repay the trouble of reproducing them.

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